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SUPERCONDUCTING AUGMENTED RAIL GUN (SARG)

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Both the energy efficiency and projectile velocity of a rail gun system can be substantially increased by the addition of an adjunct superconducting augmentation coil system. The energy efficiency results from the superconducting coil's ability to recover the rail magnetic field energy normally dissipated at the end of launch in rail guns, by means of a unique application of the flux conservation property of superconducting coils. The increased velocity results

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20. ABSTRACT (CONT'D)

from the augmented Lorentz force due to the augmentation coil magnetic field. In an idealized system, both the energy efficiency and projectile velocities can be increased by more than 80 percent, dependent on the magnetic coupling between the rail and augmentation coils. The theoretical evaluation has been extended to include dissipative effects which reveal that actual launch efficiencies are increased from 25 percent (rail gun) to over 50 percent (SARG). A theoretical analysis of SARG is presented here together with the progress of an experimental demonstrator developed at Benet Weapons Laboratory.

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INTRODUCTION

Electromagnetically launched (EML) projectiles offer the possibility of projectile muzzle velocities considerably greater than can be achieved with cannon or rocket technologies.

The most promising of EML concepts is the rail gun system due to its inherent simplicity. The development of rail gun technology, presently in its infant stage, presents many new problems which must be solved in order to complete its successful weaponization.

The major problem areas include system efficiency, Joule heating effects, switching, and power supplies. Secondary areas of concern include rail damage, projectile design, and structural integrity.

System efficiency represents the most important area since it impinges directly on all areas mentioned above as well as the important subsidiary requirements of reduction of system weight and size. Important developments have already been made on some portions of the rail gun system. The most notable in recent years is the development of compact homopolar generators (HPG). Improvements in HPG design have increased the energy stored/volume ratio by more than thirty times with a concomitant improvement in energy stored/mass ratios. Further increases in power supply performance are expected to increase these ratios by perhaps another factor of two. Thus, spectacular increases in system efficiency will occur in other portions of the rail gun system.

Figure 1 schematically suggests that such improvement might be sought in the rail gun (or barrel) itself. The rail gun represents the electromechanical load of the system and techniques must be found to increase actual launch efficiency by increasing projectile velocity to barrel length, by increasing projectile velocity to launch current ratios, and by reduction of residual magnetic

field losses at the completion of launch. Several designs have been proposed including segmented barrels and normal augmentation coils placed in series with rails. Such systems suffer from either increased difficulties of switching and timing (segmented) or increased demands on power supplies. Indeed, we have shown that normally augmented rail guns (NARG) have approximately the same efficiency as unaugmented guns under constant current operation. The increase in system performance by NARG systems is counterbalanced by increasing the source work (ref 1).

The initial study of the application of superconducting principles to rail gun design clearly showed that quantum improvements could be achieved by adding an adjunct superconducting coil operating in the persistent mode and closely coupled magnetically with the normally conducting rails (ref 1). Superconducting rails, which could have a significant effect in a space-based system but would present extraordinary commutation problems in a terrestrial system, were not analyzed. Herein we will briefly describe the previous analyses (refs 1-3), present new theoretical developments, and report on the development of the superconducting augmented rail gun (SARG) demonstrator at Benet Weapons Laboratory.

[1] C. G. Homan and W. Scholz, "Evaluation of Superconducting Augmentation on a Rail Gun System," ARRADCOM Technical Report ARLCB-TR-83016, Benet Weapons Laboratory, Watervliet, NY, June 1983.
[2] C. G. Homan and W. Scholz, "Evaluation of Superconducting Augmentation on Rail Gun Systems," IEEE Trans. on Magnetics, Mag-20, 1984, p. 366.
[3] C. G. Homan and W. Scholz, "Application of Superconductivity to Pulse Power Problems," Proceedings of the Fourth IEEE Pulsed Power Conference, (T. H. Martin and M. F. Rose, eds.), 1983.

THEORETICAL ANALYSIS

The SARG concept uses the physical principle of magnetic flux trapping of a superconducting coil. This principle may be derived by the application of Faraday's law to a closed superconducting coil of length ℓ, i.e.,

$$\oint \underline{E} \cdot d\underline{\ell} = -\frac{d\phi}{dt} = 0 \quad \text{(Superconducting Coil)} \tag{1}$$

where $\underline{E}$ is the induced electric field and ϕ is the magnetic flux threading the area enclosed by the coil.

Equation (1) is only valid for a superconducting coil, since the resistivity of a superconductor is effectively zero. By comparison, the best normal conductor, copper, has a resistivity of the order of 10^{-6} ohm cm.

Using Eq. (1), we analyzed the SARG system shown schematically in Figure 1. For the constant rail current mode of operation, we were able to show that the mechanical energy W_M, the magnetic field energy W_m, and the work required from the electrical source W_s, could be expressed by (ref 1)

$$W_M = \tfrac{1}{2} LI^2 + MII_{so} - \tfrac{1}{2} \frac{M^2 I^2}{L_s} \tag{2}$$

$$W_m = \tfrac{1}{2} LI^2 - \tfrac{1}{2} \frac{M^2 I^2}{L_s} \tag{3}$$

$$W_s = LI^2 + MII_{so} - \frac{M^2 I^2}{L_s} \tag{4}$$

In these expressions, L is self-inductance of the rail circuit; I is the normal current in the rail circuit; M is the mutual inductance between the rail and augmentation coils; I_{so} is the initial supercurrent in the augmentation coil; and L_s is the self-inductance of the augmentation coil.

[1] C. G. Homan and W. Scholz, "Evaluation of Superconducting Augmentation on a Rail Gun System," ARRADCOM Technical Report ARLCB-TR-83016, Benet Weapons Laboratory, Watervliet, NY, June 1983.

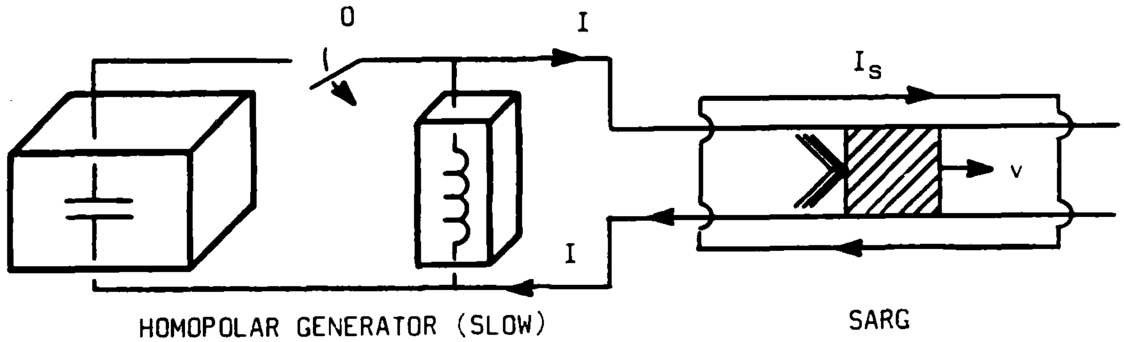

Figure 1. Schematic circuit of rail gun with an adjunct superconducting augmentation system (SARG).

Substitution of the relationship

$$M = k\sqrt{LL_s} \tag{5}$$

in Eqs. (2) through (4) yields

$$W_M = \tfrac{1}{2} LI^2(1-k^2) + kII_{so}\sqrt{LL_s} \tag{6}$$

$$W_m = \tfrac{1}{2} LI^2(1-k^2) \tag{7}$$

$$W_s = LI^2(1-k^2) + kII_{so}\sqrt{LL_s} \tag{8}$$

where k is the magnetic coupling constant and $0 \leq k \leq 1.0$.

In the derivation of Eqs. (1) through (8), we have neglected the normal resistance of the rail circuit for mathematical convenience and for a clearer explanation of the physical principles involved.

By comparison, the simple unaugmented rail gun (SRG) operating under constant current conditions yields

$$W_M = \tfrac{1}{2} LI^2 \tag{9}$$

$$W_m = \tfrac{1}{2} LI^2 \tag{10}$$

$$W_s = LI^2 \tag{11}$$

If we define the ideal launch efficiency (ILE) as ILE = W_M/W_s, then

$$ILE = \tfrac{1}{2} \qquad \text{(SRG)} \tag{12}$$

$$= \tfrac{1}{2}\,\frac{(1-k^2) + 2k\ I_{so}/I\sqrt{L_s/L}}{(1-k^2) + k\ I_{so}/I\sqrt{L_s/L}} \qquad \text{(SARG)} \tag{13}$$

again, neglecting frictional and resistance effects. Figure 2 shows the variation of ILE as a function of k.

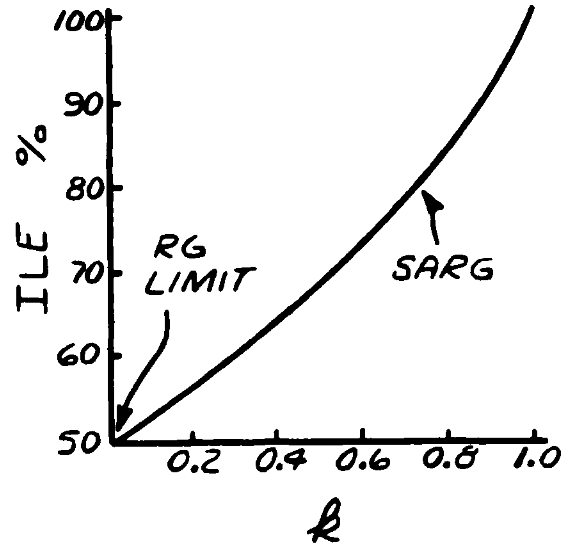

Figure 2. Variation of ideal launch efficiency (ILE) as a function of magnetic coupling constant k for the case when $I_{SO} = I$ and $L_S = L$.

So far we have dealt with ideal systems by neglecting resistance and frictional effects. We can adopt the procedure outlined by Hammond (ref 4), i.e., the system is analyzed using idealized components and then the dissipating elements are introduced. For our particular system, we note that the idealized circuit of the simple rail gun is a linear circuit in which the magnetic and mechanical energy are each equal to half of the work supplied by the source at constant current. For a nonideal system, the frictional and resistive losses can be included as a part of kinetic energy W_M. Then we may write

$$W_M = \tfrac{1}{2} m_p v_p^2 + \frac{I^2 R \Delta t}{2} + f \qquad (14)$$

[4] P. Hammond, Energy Methods in Electromagnetism, Clarendon Press, Oxford University Press, NY, 1981, Chapter 6.

where m_p and v_p are the projectile's mass and muzzle velocity, respectively; $R/2$ is the mean value of the total room temperature rail resistance; and Δt is the projectile transit time. The second term on the right of Eq. (14) is the energy loss due to current flow in the rails assuming no rail heating. The factor f contains dissipative terms due to rail heating, Joule heating, friction, etc., which are extremely difficult to analyze. Intuitively, we feel that the energy loss due to increased resistance and heat losses from rail heating will dominate f. The heating of the rails will vary as I^2, thus we expect that f will also vary as I^2 to a good approximation.

The actual launch efficiency (LE) defined as

$$LE \equiv \frac{\frac{1}{2} m_p v_p^2}{W_S} \quad \text{(SRG)} \tag{15}$$

can be determined experimentally. Thus using the experimental results of EMACK (ref 5), we estimate that LE = 25 percent and we can find using Eq. (9) that

$$\frac{W_M}{2} \approx \frac{1}{2} LI^2 \approx \frac{I^2 R \Delta t}{2} + f \quad \text{(SRG)} \tag{16}$$

In order to extend this analysis to a SARG system, we note that the adjunct superconducting augmentation system is essentially nondissipative. We assume that a SARG launcher being powered at constant current from the power source will have a dissipative term

$$f_{SARG} = f_{SRG} \cdot \frac{(I_{SARG})^2}{(I_{SRG})^2} \tag{17}$$

and that an expression of the form of Eq. (16) may be written using the appropriate W_M (Eq. (6)).

[5]D. W. Deis and D. W. Scherbarth, "EMACK Electromagnetic Launcher Commissioning," IEEE Trans. on Magnetics, Mag-20, 1984, p. 245.

This assumption cannot be justified on the basis of SARG being a linear circuit, since Eqs. (6) and (7) clearly show that equipartition does not occur in SARG. However, the magnetic energy of a SARG operating at constant current depends only on the specific inductances of the circuit and thus is a function of system geometries only. Therefore, the dissipative terms are clearly related to the kinetic energy team.

SARG DEMONSTRATOR

In order to demonstrate the principle of superconducting augmentation, Benet Weapons Laboratory (BWL) and Los Alamos National Laboratory (LANL) are collaborating in the construction and test of a SARG demonstrator.

LANL is constructing and testing a small rail gun system consisting of a 1 meter long, 3/8-inch square bore rail gun powered by a 5 Kv, 1444 μf capacitive energy source through a 6 μH pulse shaping inductance. A 4 gram projectile should reach a muzzle velocity of at least 600 m/sec in this gun. Recently, LANL launched fifty projectiles at various power levels and measured muzzle velocities with flash x-ray techniques. Statistically significant velocity results will be reported for the various power levels.

Benet is modifying a 4 Tesla superconducting dipole magnet system, supplied by DOE from the ESCAR Magnet Program, to a warm bore configuration. The modified magnet coupled with Benet's 20 watt liquid helium (LHE) refrigerator system constitute the adjunct augmentation system. The augmentation system was completed and tested in FY86.

The SARG system will be assembled from these components and tested in FY87. The assembled SARG will have relatively low magnetic coupling ($k \sim 0.4$) due to the particular design of the ESCAR magnet system. However, a properly designed SARG system discussed below should be able to achieve coupling constants greater than 0.9.

The present demonstrator system should yield a 50 percent increase in muzzle velocities and more than 50 percent increase in actual launch efficiencies at equivalent power supply levels.

Cryogenic testing of the ESCAR magnet system by DOE indicates cryogenic loads of less than five watts at 4.5 K using closed-cycle refrigeration and with heat loads approaching launch conditions. Thus, the capability of providing adequate refrigeration from small scale, commercially available units is feasible. This point is central to the weaponization of SARG systems.

PROTOTYPE SARG WEAPONS

The weaponization of SARG launchers will require solutions to technical problems unique to these new systems. Benet is particularly concerned with those problems associated with direct fire or close combat weaponization. Typical specifications of such a system are shown in Table I.

Additional problems associated with a SARG-type system include improvement in coupling coefficients, cryogenic requirements, superconducting magnet quench due to eddy current heating or exceeding the critical temperature, magnetic field or current of the superconductor used, and the mechanical integrity of the augmentation system itself.

TABLE I. TYPICAL SPECIFICATIONS FOR THE WEAPONIZATION OF A SARG LAUNCHER

Total Mass of Projectile and Sabot	> 3 kg
Projectile Muzzle Velocities	> 3 km/sec
Projectile Energy	> 13.5 MJ
Barrel Length	< 8 m
System Weight (including vehicle)	< 55 tons
Firing Rate	> 1 Hz

A feasibility study was performed to determine if a SARG-type system could meet these specifications using existing technology. That is, what would be the most feasible configuration of a rail launcher using components and technologies presently available.

Before describing the results of the analysis, we will present some solutions to problems directly concerning SARG configurations.

The magnetic quenching of a properly designed superconducting coil occurs primarily by eddy current heating of the copper matrix material in commercially available superconducting wire. The present state of the art cable when ramped with current from an external source can sustain 60 Hz cycling without quenching. This translates into a half period of about 8 msec which represents the limit of its use in a rail gun application. Since transit times of the rail gun described here are in the order of 4 msec, use of a superconducting coil ramped with current from an external source is not possible with present technology.

However, in the SARG configuration, the augmentation coils are a closed loop with persistent supercurrents. Hence, SARG augmentation coils are ramped by the magnetic field of the rails. This is an entirely different physical

situation from current ramping. Unfortunately, no experimental data exists for this situation; however, considering the magnetic flux conservation stated in Eq. (1), one would expect that eddy current heating would be substantially reduced. Of course, a coil completely composed of superconducting filaments would have no eddy current heating. Coils made from commercially available cable require at least ten percent of the cable volume to be copper matrix for conduction, fabrication, and mechanical reasons. The half period for magnetic ramping of a 90 percent superconducting - ten percent copper matrix cable coil was estimated to be at least a factor of two less than the current ramp case (ref 6). This estimate suggests a SARG-type system in which the supercurrent is ramped by the magnetic field of the rails may be marginally possible.

To further reduce the possibility of magnetic field ramp quenching, we analyzed the "ballasted" SARG circuit. The "ballasted" SARG is constructed by placing an additional superconducting coil in series with the augmenting coil which is not magnetically coupled with either the augmentation or rail coils. Such a configuration is shown schematically in Figure 3.

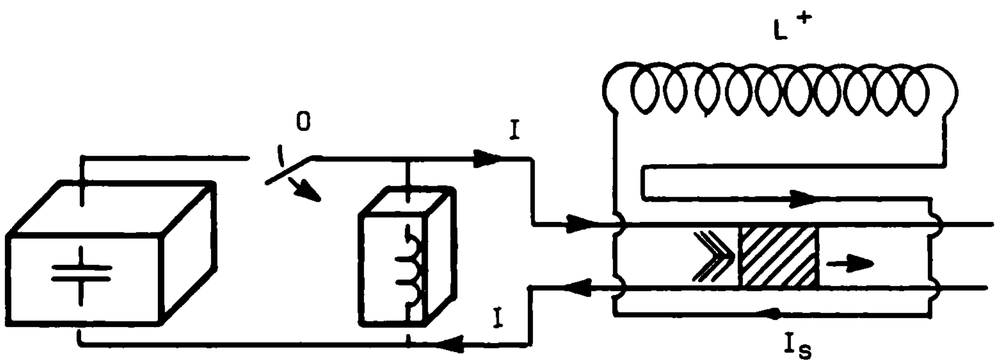

Figure 3. Schematic circuit of "ballasted" SARG.

[6]T. Pollock, Private communication, Intermagnetics General Corporation, Guilderland, NY, 1986.

Now the inductance of the superconducting circuit L^* is $L^* = L^+ + L_s$, where L^+ is the inductance of the "ballast" coil and L_s is the inductance of the augmentation coil. Also, if $L^+ >> L_s$, then

$$L^* = L^+ + L_s >> L_s \tag{18}$$

and

$$M = k\sqrt{LL_s} \tag{19}$$

We have previously shown (ref 1) for the "ballasted" SARG that

$$W_M = \tfrac{1}{2} LI^2 + LII_{so} \frac{M}{L} = \tfrac{1}{2} LI^2[1 + \frac{2I_{so}}{I} k \sqrt{\frac{L_s}{L}}] \tag{20}$$

$$W_m = \tfrac{1}{2} LI^2 \tag{21}$$

$$W_s = LI^2 + LI_{so}I \frac{M}{L} = LI^2[1 + \frac{I_{so}}{I} k \sqrt{\frac{L_s}{L}}] \tag{22}$$

Evaluation of the supercurrents shows

$$(I_s)_{SARG} = I_{so} = \frac{IM}{L_s} \tag{23}$$

and

$$(I_s)_{BALLASTED\ SARG} \approx I_{so} \approx \text{Constant} \tag{24}$$

Thus, the ramping of the supercurrent which occurs in SARG may be significantly reduced in the ballasted SARG condition.

In order to evaluate the three systems involved, we used the procedure outlined in Eqs. (14) through (17) to determine f for each system; Eqs. (6) through (8) for SRG; Eqs. (9) through (11) for SARG; and Eqs. (20) through (22) for the "ballasted" SARG to determine system parameters. Assuming a constant projectile energy of 14 MJ, these parameters are tabulated in Table II.

[1]C. G. Homan and W. Scholz, "Evaluation of Superconducting Augmentation on a Rail Gun System," ARRADCOM Technical Report ARLCB-TR-83016, Benet Weapons Laboratory, Watervliet, NY, June 1983.

TABLE II. RESULTS OF THE THEORETICAL ANALYSES OF THREE CONFIGURATIONS OF RAIL LAUNCHERS (RAIL GUN, SARG, AND BALLASTED SARG). THESE CALCULATIONS WERE PERFORMED HOLDING PROJECTILE VELOCITY CONSTANT.

	I(MA)	I_{so}(MA)	$\frac{1}{2}m_p v_p^2$(MJ)	$I^2R\Delta t/2+f$ (MJ)	W_m(MJ)	W_s(MJ)	Act Eff %
Rail Gun	3.9	NA	14	14	28	56	25
SARG	3.1	0.61	14	8.5	3.2	25.7	54
Ballasted SARG	2.2	0.44	14	4.2	8.6	26.8	52

In these calculations, we assumed that I was constant, $L = 3.6 \times 10^{-6}$ Henry, $R = 2.4 \times 10^{-4}$ ohms, and the transit time $\Delta t = 4$ msec from the experimental EMACK test results (ref 5). In addition, we assumed the conservative values of k = 0.9, $L_s = 10$ L, and $I = 5\ I_{so}$ for the augmentation system.

These results indicate that the actual efficiency of an augmented system is more than twice that of a simple rail gun. The ballasted SARG is the superior design for the following reasons.

1. The current required is 30 percent less than SARG and 44 percent less than SRG. Thus, heating loads and cooling requirements are significantly lowered.

2. For approximately the same size source and efficiencies, the ballasted SARG has significantly higher magnetic field energy than SARG which must be dissipated. However, this energy is dissipated after launch and may be more efficiently disposed in either a properly designed muzzle resistor or may actually be partially recovered. The magnetic field energy is only 30 percent of the SRG configuration.

[5] D. M. Deis and D. W. Scherbarth, "EMACK Electromagnetic Launcher Commissioning," IEEE Trans. on Magnetics, Mag-20, 1984, p. 245.

It is important to note that the kinetic energy used is sufficient to launch penetrator type projectiles (3 kg) at velocities greater (3 km/sec) than achievable by current cannon.

Some important tradeoffs must be considered. For example, the increased complexity of superconducting coil and cryogenic requirements for the augmented systems are offset by increased efficiency and lower rail heating.

The increased efficiency means that smaller homopolar generators (or other power supplies) may be used to power the launcher system. Present HPG's weigh, with their ancillary equipment, approximately five tons and can deliver about 1 MA to a rail gun system load. Thus the power supply requirement, assuming an increase in HPG efficiency of 25 percent would lead to power supply weights of over 15 tons for an SRG and over 12 tons for SARG, compared to about 9 tons for the ballasted SARG case.

One must consider the additional weights of the augmentation system including the cryogenic and power modules. From our preliminary experimental results on the SARG demonstrator, we can estimate cooling loads of about 10 watts at 4.5 K. Thus, the ancillary equipment to the augmented systems should weigh less than two tons.

The weight of the augmentation ancillary equipment will be offset by the reduced cooling requirement of the rail gun when operated in these modes, since less than 30 percent of the waste heat generated by an SRG launch is developed in a ballasted SARG launch.

CONCLUSION

Application of superconducting technology to the augmentation of simple rail guns can yield significantly improved efficiency. This improvement is achieved by reducing both the magnetic field normally dissipated at the end of launch and the barrel Joule heating losses.

This study also indicates that it is practical to achieve weapon quality launchers using current state of the art technology with mobile gun systems.

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